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Control of indoor CO_2 concentration based on a process model

Igor Škrjanc [b,*], Barbara Šubic [a]

[a] Faculty of Civil Engineering, University of Ljubljana, Ljubljana, Jamova 2, 1000 Slovenia
[b] Faculty of Electrical Engineering, University of Ljubljana, Ljubljana, Tržaška 25, 1000 Slovenia

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ABSTRACT

Air-tight buildings need to have ventilation systems, although the use of these systems results in heavy energy consumption within the building sector. For this reason they have to be adequately regulated in order to achieve good indoor air quality and lower operation costs. The main challenge is to optimize regulation in office buildings, theaters, museums, and schools, where there are large fluctuations and heavy operating costs. Each further optimization leads directly to a better indoor climate and a reduction in energy consumption. In the case of ventilation systems, PI or PID regulators are usually used. In the described research an internal model control (IMC) system was designed with an internal loop, which constantly checks the momentary CO_2 concentration, and makes the necessary adjustments to the air flow. The results showed a significant improvement in the CO_2 level when using an IMC controller, in comparison with PI controller. The desired indoor air quality is achieved more than 80% of the time, with lower operating costs.

1. Introduction

Within the EU, more than 40% of produced energy is used by the building sector, which is responsible for 35% of CO_2 emissions. At least 20% of all energy is used for the heating, cooling and ventilating of buildings (Heating, ventilation and air conditioning systems — HVAC, [16]). Over the years HVAC systems have changed significantly. While human comfort in buildings has been much improved by means of different HVAC systems, energy consumption has also risen. It is generally recognized that, while improved technical solutions are very desirable, at the same time energy consumption needs to be reduced. A number of steps have been taken in this direction, such as: improved thermal insulation of walls and roofs and improved windows, pump-heating systems and central ventilation systems. The energy consumption of buildings is the main issue. However, many of the steps which have been taken lower energy consumption also result in a decrease in the level of human comfort. For example triple glazing, which is nowadays most commonly used in new buildings, reduces the energy consumption of a building, but simultaneously reduces light transmission. It has been shown that the amount of natural light in a room has a significant effect on the productivity and well-being of people using it [6]. It has also been shown that ventilating systems or shading systems, which do not permit any user interference, are not optimal for users [22]. Such systems cannot usually respond quickly, or even at all, to changeable room conditions. Over the last decade low energy solutions have remained the main goal, but greater emphasis has been placed on human comfort and well-being.

Despite the fact that systems for thermal comfort, air-quality and lighting need to be designed and solved together [12,13],the authors have attempted to go deeper into research of only air-quality regulations, with the aim of finding regulation solutions which can respond to momentary air quality in rooms and buildings. The results of this research could be implemented in collective regulation systems.

Nowadays ventilation systems are practically indispensable in all buildings. Many researchers have found a strong correlation between ventilation strategies, indoor air quality (IAQ), and energy consumption. For instance, Budaiwi [5] compared different ventilation strategies, i.e. continuous ventilation, ventilation only during occupancy, and ventilation based on variable occupancy. He showed that in the case of ventilation only during occupancy, and ventilation based on variable occupancy, there was a decrease in energy consumption of 30% and 50% respectively, compared to continuous ventilation. It has also been shown that ventilation in buildings is often designed and used for maximum occupancy, which, realistically, is hardly ever achieved [7]. If ventilation systems are not adequately adjusted to real needs, the energy losses can be huge. Several authors have suggested that a CO_2 parameter could be suitable parameter for detecting the level of occupancy, and for the adjustment of the ventilation rate [7,11,13,14,15,21]. Different percentages of energy reduction (ranging from 10 to 50%) are cited in the case of demand control ventilation (DCV) as compared to continuous ventilation. In the U.S. Department of Energy (Energy Efficiency and Renewable Energy) a relationship has been established between the ventilation rate and the CO_2 concentration. According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the ventilation rate should be set as 25.5–34 m^3/h/person. At this rate the

* Corresponding author.
E-mail addresses: igor.skrjanc@fe.uni-lj.si (I. Škrjanc), Barbara.Subic@m-sora.si (B. Šubic).

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CO_2 concentration in a room could not exceed 1000 ppm, which is the limit set by the ASHRAE as a standard value.

If the DCV system is selected as a regulating tool, then its effectiveness depends on the speed of its reaction to real-life changes. Some models react faster and better than others. If such models are finely tuned, it is possible to decrease energy consumption even further. The effectiveness of DCV can be an even greater role in the case of buildings where large and sudden fluctuations are expected, e.g. in museums, theaters, and galleries. The main goal is the management of fast adjustments to the ventilation rate. If this is not achieved then, despite the detection of an increased CO_2 concentration detection and the activation of the ventilation system, it might happen that the rate of ventilation is not adjusted to the real need. This could lead to a stage where a comfortable level of air conditioning (with CO_2 lower than 1000 ppm) is achieved over an excessively long response-time, or frequently not at all. Ventilation systems which have the same response whether a gallery is quite full of half empty are not appropriate.

The type of regulation used in the case of various HVAC systems differs. The use of linear regulators (proportional (P), integral (I) and also derivative (D)), as well as nonlinear regulators, or combinations of both, has been described in the literature ([2,4,12,24]). Despite the fact that HVAC systems are nonlinear systems, they can be satisfactorily controlled by means of linear regulators [10,18,19]. A method for signal filtering used in the PID controller, which significantly improve the properties of the feedback loop, has been presented by Hägglund [9]. Filters were established for the set-point, the process output, and the measurable load disturbance. By means of filters it is possible to improve process models by up to 25%. In this paper the design of a PI controller based such a process model is presented. An anti-windup mechanism was also implemented, which is needed if the control system is to function properly, and is strongly influenced by constraints. The paper is organized as follows: a problem description and mathematical model are given in Section 2, whereas in Section 3 the design of the control algorithm is presented. Simulation of control systems is presented in Section 4 and conclusions are given in Section 5.

2. Problem description and mathematical model

In all buildings where the occupancy of rooms is not constant and can fluctuate massively, e.g. schools, office buildings, theaters, and museums, the regulation of air ventilation is a difficult problem. In most cases the ventilation systems have several rates on which they can work, and these rates have pre-defined activation schedules. However, such regulation systems cannot react to momentary changes in the room. Regulation systems react on the on–off principle. They are therefore not optimal, and cannot provide healthy air conditions inside the room. Buildings are often under or over ventilated, without disregard to the real rate of occupancy. Over-ventilated buildings are not cost-effective, whereas under-ventilated buildings lead to health problems [16]. In the case of short term exposure these consist of headaches, drowsiness, lack of concentration, fatigue, nausea, and dizziness. In the case of long term exposure the health problems could be: eye, nose and throat irritations, air-way infections, and coughs. In this paper a description is given of a ventilation system which is able to regulate air flow with the aim of CO_2 reduction, according to the needs in the room. Similar models have been described by Aglan [1], and Shi et al. [17]. The model describes the changes in the CO_2 concentration in the room directly in dependence on the level of occupancy, i.e. the number of people inside the room. It includes the intake of outdoor fresh air (q), the CO_2 concentration of the outdoor air (c_0), the concentration of CO_2 exhaled by the people in the room (p), and the outflow which is equal to the intake flow (q) with current CO_2 concentration (c) (Table 1). The model is based on the assumption that the CO_2 concentration of the outdoor air is constant and known, and that the indoor reference concentration of CO_2 is also defined. The volume of the space is defined as V.

Table 1
Nomenclature.

Variable	Description	Unit
q	Outdoor fresh air intake	m^3/h
q^*	Outdoor fresh air intake in steady-state	m^3/h
q_c	Constraint signal	m^3/h
q_{min}	Minimal airflow rate	m^3/h
q_{max}	Maximal airflow rate	m^3/h
c_o	Outdoor air CO_2 concentration	ppm
c	Momentary CO_2 concentration	ppm
c^*	Concentration of CO_2 in steady-state	ppm
c_r	Reference CO_2 concentration	ppm
c_m	CO_2 concentration as the model output	ppm
ph	CO_2 concentration generated per person	ppm*m^3/hperson
p	CO_2 concentration generated by all people in the room	ppm*m^3/h
$G_m(s)$	Transfer function of the process model	
$G_r(s)$	Transfer function of the reference model	
$G_c(s)$	Transfer function of the controller	
T_r	Reference model time constant	h
V	Room model volume	m^3
N	Number of people in the room	
t	Time	h

The equation which defines the change of concentration in the room is the following:

$$\frac{dc}{dt} = \frac{c_0}{V}q - \frac{1}{V}cq + \frac{1}{V}p. \tag{1}$$

The change of CO_2 concentration depends nonlinearly on intake flow q, the indoor CO_2 concentration c, and the exhaled CO_2 concentration of the people in the room p. It can be rewritten as a nonlinear differential equation as follows

$$\frac{dc}{dt} = f(c, q, p). \tag{2}$$

The concentration c can be controlled by the intake flow q. This means that the concentration c is the controlled variable (CV), whereas the intake flow q is the manipulated variable (MV). The exhaled concentration p is not measurable, and is therefore treated as a disturbance.

3. Linearization and controller design

The design of a linear controller requires the use of a linear model of the process in the equilibrium point or in the operating point. The nonlinear model of the process is therefore described, in a linearized form as follows

$$\frac{dc}{dt} = \left.\frac{\partial f}{\partial c}\right|_{(c^*,q^*)} c + \left.\frac{\partial f}{\partial q}\right|_{(c^*,q^*)} q \tag{3}$$

where c^* and q^* denote the equilibrium point for concentration c and for intake flow q, respectively.

In order to define the deviation model, the equilibrium point first need to be found. This means that the derivative at this point is equal to zero, as shown:

$$f(c, q, p)\Big|_{(c^*,q^*)} = 0. \tag{4}$$

This gives us a relation between the input and output of the process when in equilibrium, or in steady-state. The relation is presented in Fig. 1 and defined in Eq. (5).

$$q^* = \frac{-p}{c_0 - c^*}. \tag{5}$$